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Exploring Potential of Energy Flexibility in Buildings for Energy System Services

Rongling Li and Shi You

***Abstract*—Buildings have both high as well as flexible energy demands and play an important role in the energy internet solution. The buildings' energy flexibility (BEF) is a widely recognized concept; however, how to unlock its potential is a relatively new research topic. In this paper, the authors provide an overview of the latest research related to BEF. An introduction to BEF is provided, methods developed for identifying and characterizing BEF are presented, and several key influencing factors are identified. The overview also covers various aggregation methods to scale up BEF impacts and service-oriented solutions for enabling BEF applications in different energy sectors. This work lays the groundwork for designing and developing seamless integration strategies for BEF use in both present and future energy systems.**

***Index Terms*—Aggregation, buildings' energy flexibility (BEF), energy internet, seamless integration, service-oriented framework.**

I. Introduction

THE penetration of renewable energy resources is increasing rapidly. In EU countries, at least 20% of total energy demand must come from renewables by 2020 [1]. Denmark plans to have 50% of its energy demand covered by wind power by 2020 [2]. High penetration of intermittent renewables makes the power system today in desperate need of flexibility. In recent years, rapid development of information and communication technologies (ICT) [3] has led to a transformation towards an energy internet, wherein various decentralized, efficient, reliable, user-friendly and cross-sectoral (optional) energy solutions actively function together to fulfill the desire of a future green energy society.

In most developed countries, buildings account for one third of total energy consumption. They are a crucial element in the energy internet solution due to their role of coupling different energy sectors on the demand side and at the same time offering considerable potential for flexible energy consumptions as energy system services. Thermal energy storage in heating systems inside buildings, and building thermal mass have major energy flexibility potential, although this capacity is case-specific depending on the type of storage and their heating, ventilation, and air-conditioning (HVAC) systems [4], [5]. A simulation study of a single-family house has shown that the energy flexibility of the house represents approximately 5.5% of its annual heating load. Given the increasing possibility of the adoption of energy flexible buildings and their flexible operation in many European countries, with use of demand response control coupled with thermal storage, buildings can contribute to power system flexibility, district heating (DH) grid flexibility, and reduction of the carbon footprint of the building stock [6].

In order to make best use of a building's energy flexibility, it is particularly important to identify and characterize its BEF [7], [8]. The process of identification helps to quantify the amount of flexibility available in an individual building or a building cluster by pointing out sources of flexibility and limiting factors. The process of characterization describes the technical properties of BEF following standardized ontologies, thus enabling a seamless integration of flexibility into the operation of various energy systems. This paper aims at presenting an overview of recent research conducted on the exploitation of BEF, particularly related to identification and characterization approaches. In Section 2, various understandings of buildings' energy flexibility are introduced. Section 3 presents an overview of methods developed for identifying and characterizing a building's energy flexibility, including highlighting a number of key influencing factors. Section 4 explains various aggregation-based modelling methods with examples. Service-oriented solutions for enabling the seamless integration of BEF into energy system operation as energy system services are given in Section 5. Section 6 presents concluding remarks and future work.

II. Definition of Buildings' Energy Flexibility

A definition of BEF in a broad sense has been made by International Energy Agency (IEA) Energy in Buildings and Communities Programmes (EBC) Annex 67 Energy Flexibility in Buildings [9], "The Energy Flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements (Fig. 1). Energy Flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements."

Another conceptual definition in [10] is that the flexibility of building is the ability to deviate from its reference electric load profile, which is also referred to as electrical flexibility. The definition of electrical flexibility can also be case dependent, such as in [11], where electrical flexibility is defined as the

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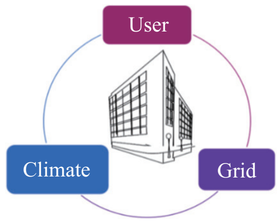

Fig. 1. Three elements in the definition of the energy flexibility in buildings.

ability to shift the heat pump electric load from peak to off-peak hours based on electricity price.

Towards the utilization of buildings' heat flexibility in DH grids, a heat/thermal flexibility indicator has been developed, as described in [12]. In this study, heat supply is turned off during peak demand hours while indoor temperature remains higher than predefined the minimum comfortable temperature threshold. The time duration from the moment the heat supply is switched off until the indoor operative temperature decreases to the threshold is defined as the heat/thermal flexibility.

III. Identification and Characterization of BEF

A. Methodology

The energy flexibility of buildings can be identified and characterized using two methods – either from the perspective of appliances inside the buildings or from the perspective of a whole building. The former method normally takes building parameters (such as the thermal mass of a building's envelope) as thermal constraints that can limit the amount of the flexibility offered by HVAC appliances in the buildings. The latter method considers the whole building as a synthetic element and merges all flexibility options within the building into one.

In addition, the BEF can be characterized from either an electrical aspect or a heat aspect as introduced in the previous section. The electrical flexibility comes from both electrical appliances for non-HAVC purposes and those for HVAC purposes, while the latter type is heavily limited by the thermal characteristics of the buildings.

The most common parameters in the characterization of BEF are the amount of change in energy demand, the power change, the duration of the change, the response time, and the shifted load [13]. A brief review of methodologies for assessing BEF reveals that energy flexibility is quantified as the deviation of electricity consumption under different scenarios. while taking into account electricity related costs or thermal comfort schemes [14]. The building occupants' thermal comfort is a constraint of flexible operation; as such this has become a common approach for calculating energy flexibility of buildings, especially HVAC systems and thermal mass, based on pre-defined upper and lower temperature bounds, such as in [6] and [15]. For the characterization, the common approaches to be adopted will be modelling, simulation, and real-life measurements.

Modelling and simulation are the prime measure in this study, since measuring the related properties can be complex and very time-consuming. In [16] the demand flexibility concept is proposed for non-residential buildings (Fig. 2). Flexible power is defined as power that is shifted or shed in response to a request from the grid, which is either up regulation (increase in power demand) or down regulation (decrease in power demand).

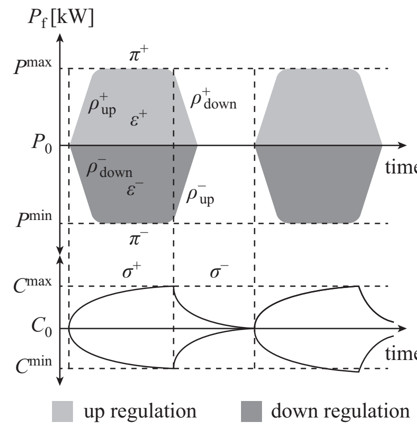

Fig. 2. Demand flexibility metrics, P_f: flexible power, C: thermal comfort [16].

In [17] two residential buildings with different levels of insulation and air-tightness are modelled, and their performance in terms of heat storage and heat conservation is investigated. Flexibility is defined as the ability to shift energy use from high price periods to low periods. Equation 1 shows how to calculate this flexibility factor indicated by *Flex*, considering instant heating demand q_{th} and high and low electricity price periods expressed by t_{ph} and t_{pl} respectively. The spot market price in a week was observed to make divisions for high, medium, and low electricity price intervals. According to the equation, the flexibility is 0 if the heating use is similar in low and high price periods; 1 if no heating is used in high price periods; and -1 if no heating is used in low price periods.

$$Flex = \frac{\int_{t_{\mathrm{pl}}} q_{\mathrm{th}}\mathrm{d}t - \int_{t_{\mathrm{ph}}} q_{\mathrm{th}}\mathrm{d}t}{\int_{t_{\mathrm{pl}}} q_{\mathrm{th}}\mathrm{d}t + \int_{t_{\mathrm{ph}}} q_{\mathrm{th}}\mathrm{d}t} \tag{1}$$

In [10] the buildings are a supplier of electrical flexibility services through demand side management. Cost curves of these services are computed, showing the amount of flexibility and their associated cost. Here, energy flexibility is defined based on a reference scenario, which is the optimal operation of building energy systems. The maximal positive flexibility $\Phi_\uparrow$ and maximal negative flexibility $\Phi_\downarrow$ are defined as Equation 2 and 3.

$$\Phi_\uparrow = E_{\mathrm{max}} - E_{\mathrm{ref}} \geq 0 \tag{2}$$

$$\Phi_\downarrow = E_{\mathrm{min}} - E_{\mathrm{ref}} \geq 0 \tag{3}$$

Different storage options, such as batteries, fuel switch, water tanks, phase change material tanks, thermochemical material tanks, and thermal building mass for office buildings are carried out to enhance the grid-supportive operations in the energy supply system [18], [19]. In [18] two indicators are defined: absolute grid support coefficient and relative grid support coefficient.

$$GSC_{abs}(G) = \frac{\sum_{i=1}^{n} W_{\mathrm{el}}^{i} \cdot G^{i}}{W_{\mathrm{el}} \cdot \bar{G}} \tag{4}$$

$$GSC_{\mathrm{rel}} = 200 \cdot \frac{GSC_{abs}(PB_l) - GSC_{abs}^{*}}{GSC_{abs}(PB_l) - GSC_{abs}(PB_u)} - 100 \tag{5}$$

where W_{el}^{i} is the electricity consumption in time step i, G^i is the value of the grid signal in time step i, and n is the total number of time steps. GSC_{abs} represents an energy system view, which can be used to evaluate the grid impact of a building or its heating system. GSC_{rel} shows the building operation perspective, which can be used to assess the optimization potential for heating or cooling system operation. PB_l, PB_u indicate the potential boundaries determined by rescheduling the electricity consumption of each to either the most favourable case or the least favourable case in terms of the grid signal respectively. GSC_{abs}^{*} denotes the achieved value of GSC_{abs}.

The authors in [11] have proposed an approach that quantifies flexibility of space heating demand in terms of electricity cost. This approach characterizes flexibility as the ability to shift the heat pump electricity loads from peak period to off-peak period, and represents the flexibility factor ff as a function of the discrepancy of maximum and minimum procurement cost, as shown by Equations 6-9. With these equations, the average cost of electricity $P_{\mathrm{el,avg}}$ is defined, and $P_{\mathrm{el,max}}$ and $P_{\mathrm{el,min}}$ are calculated using the maximum and minimum hourly electricity price of the current day, with the integration performed over the whole year. $C_{\mathrm{el,avg}}$ is the actual average unit cost during the period without any load shifting, and $C_{\mathrm{el,max}}$, $C_{\mathrm{el,min}}$ are the procurement costs that occur when loads are shifted towards minimal or maximal pricing.

$$C_{\mathrm{el,avg}} = \frac{\int_0^t P_{\mathrm{el}} \times W_{\mathrm{el}} \mathrm{dt}}{\int_0^t W_{\mathrm{el}} \mathrm{dt}} \tag{6}$$

$$C_{\mathrm{el,max}} = \frac{\int_0^t P_{\mathrm{el,max}} \times W_{\mathrm{el}} \mathrm{dt}}{\int_0^t W_{\mathrm{el}} \mathrm{dt}} \tag{7}$$

$$C_{\mathrm{el,min}} = \frac{\int_0^t P_{\mathrm{el,min}} \times W_{\mathrm{el}} \mathrm{dt}}{\int_0^t W_{\mathrm{el}} \mathrm{dt}} \tag{8}$$

$$ff = \frac{C_{\mathrm{el,max}} - C_{\mathrm{el,avg}}}{C_{\mathrm{el,max}} - C_{\mathrm{el,min}}} \tag{9}$$

where P_{el}, $P_{\mathrm{el,min}}$, $P_{\mathrm{el,max}}$ are average, minimum, and maximum hourly electricity price (€/kWh); $C_{\mathrm{el,avg}}$, $C_{\mathrm{el,min}}$, $C_{\mathrm{el,max}}$ are average, minimum, and maximum unit cost of the electricity consumed by the heat pump (€/kWh) respectively; W_{el} is the electrical power of the heat pump compressor (W).

In modern urban design, buildings are tending to have high window-to-wall ratio. A newly constructed apartment building located in Copenhagen by the seaside has the window to wall ratio of 72%. With such configuration, the external wall thermal mass is not influential on the load shifting potential in comparison with the internal walls [20].

Real-life measurements are, in general, conducted to investigate electrical flexibility of home appliances. The flexibility potential of five smart appliances, i.e., washing machines, tumble dryers, dishwashers, domestic hot water tanks, and electric vehicles was tested in the LINEAR pilot project in Belgium [21]. A method for quantifying the energy flexibility of home appliances was also proposed (Fig. 3) for (a) increased power consumption (P_{inc}) and (b) decreased power consumption (P_{dec}). The flexibility potential was defined as "the P_{inc} and P_{dec} that can be realized at a certain time of day, combined with how long the power increases or decreases can be sustained (Δt)".

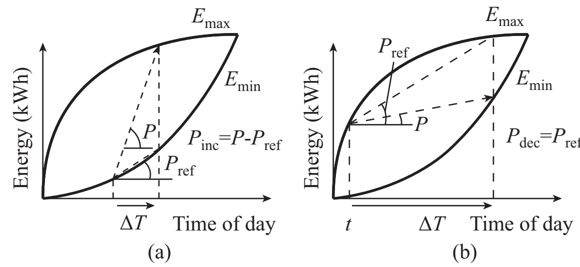

Fig. 3. Flexibility potential calculation for smart home appliances presented in [21]. $E_{\max}$ and $E_{\min}$ represent the power consumption of appliances when they consume energy at the earliest possible time and at the latest possible time, respectively.

A longitudinal study was conducted in the Netherlands to explore the electricity demand shift in 77 Dutch households. These households were equipped with solar panels, a smart washing machine and an energy management system that gave feed forward on dynamic prices [22].

Laboratory tests and field measurements were also done in some studies of thermal storage of buildings and heat pump systems within buildings. Four key indicators have been developed in [23] that reflect the flexibility state of domestic hot water buffers. These buffers have also been validated by means of simulation and laboratory tests. A pilot test was conducted in [24] on the thermal energy storage in building thermal mass. The concepts of time constant and degree hour were proposed as good indicators. The time constant of a building is directly related to the building's thermal mass; this describes how fast a building will be affected by an adjustment in heat delivery. The degree hour value indicates the quantity of thermal energy that can be stored in the building. The study concludes that with an increase in insulation level, the time constant also increases, whereas the heating energy demand decreases. A lab test was set up to examine the potential of a heat pump system for demand response in a single family house in [25]. The controller that was designed for the test was able to shave electrical energy peaks and enable self-consumption of locally produced electricity.

In terms of the whole building scale, in [26] the authors attempted to test and measure flexibility in an office building to ensure that the thermal comfort of building occupants would not be disturbed. However, the team faced issues in that most of the building energy systems could not be overridden from the central control for assessing energy flexibility. It was concluded that the installation of automation systems on building energy systems is a prerequisite for assessing and utilizing the energy flexibility of buildings in practice.

B. Types of Building and Modelling Methods

Table I provides a brief summary of building types and modelling method in the simulation studies of exploring BEF. White box models developed in building simulation software are commonly used to assess the potential of BEF, in which rule-based control is normally implemented. Resistor-capacitor RC circuit models are used in the studies when optimization and advanced control, such as optimal control and model predictive control, are implemented and demonstrated [27]. The other model type that is commonly used in the research of building energy performance, black box model, was rarely used in the study of energy flexibility of buildings. Black box models are fitted statistical models usually based on large datasets from measurements. As energy flexibility is not a characteristic that can be measured during the normal operation of buildings, there is still limited data collection. Therefore, this approach has not been used. However, black box modelling has been found used at a later stage when a large database is generated using building simulation tools [12], [28]. The statistical models are then used for performance prediction.

TABLE I
THREE ELEMENTS IN THE DEFINITION OF THE ENERGY FLEXIBILITY IN BUILDINGS

Literature	Building type	Energy type[1]	White box	Grey box
[10], [18], [29]	Commercial	Electrical		RC for building
[12]	Residential	Thermal	TRNSYS	
[17]	Residential	Thermal	Energy+	
[30]	Residential	Thermal	Modelica	
[11]	Residential	Electrical		RC for building
[16]	Commercial	Electrical	Energy+	
[19]	Commercial	Thermal and Electrical	Numerical model for TES[2] tanks	RC for building
[28]	Residential & Commercial	Electrical	Energy+ for building	RC for appliance

[1]Energy type stands for the type of energy flexibility – thermal or electrical flexibility, investigated in the referred study. [2]TES stands for thermal energy storage. Energy+ stands for the software EnergyPlus.

So far, most studies on residential buildings have focused on thermal energy flexibility of heating system and building thermal mass. There are a few studies about electrical flexibility in office buildings, such as in [16], [28]. In [16], office BEF in hot humid (ASHRAE 2A) and cool humid (ASHRAE 5A) climates was evaluated. The EnergyPlus software was used as the platform for this study as it provides typical building types and models with ASHRAE standards integrated. The methodology is shown in Fig. 4, which includes detailed steps for the quantification of energy flexibility. This method is representative of simulation-based energy flexibility studies.

A framework is presented in [28] for the estimation of residential and commercial buildings' energy flexibility (Fig. 5). EnergyPlus was used for building modelling, and RC models were developed for HVAC systems. EnergyPlus embedded prototype reference models of commercial and multi-dwelling residential buildings in different climate zones were also used. The simulations generated more than 300 million data points.

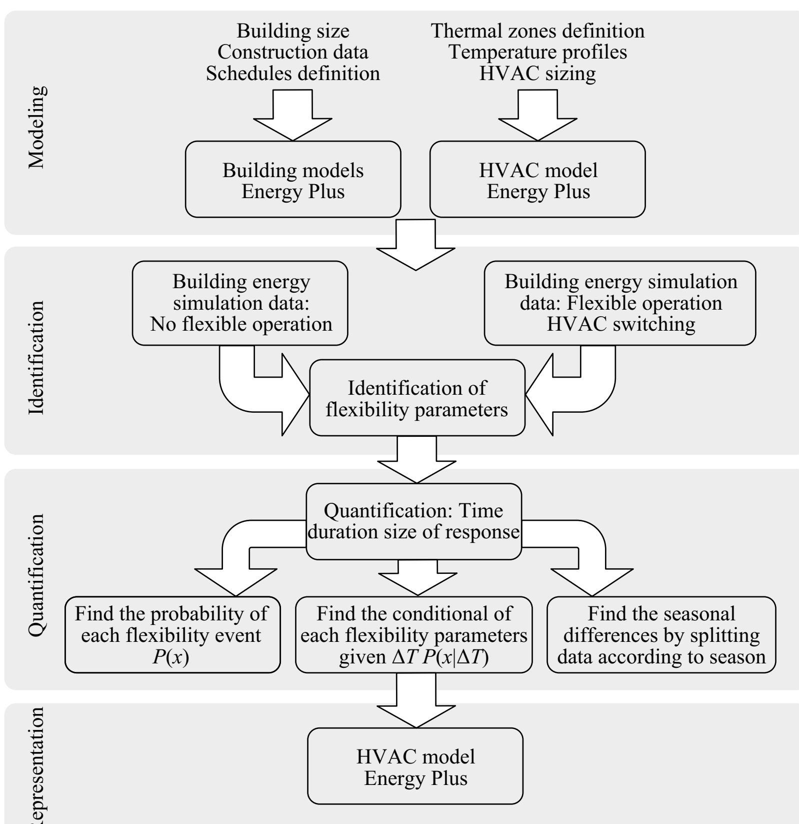

Fig. 4. Quantification method presented in [16].

Using this dataset, regression models were fitted to predict demand response potential based on hour of day, set point change, and outside air temperature. The application of the framework was demonstrated with two case studies. The results show that the framework was valuable both for predicting peak load shedding potential of an individual building and for estimating aggregated energy flexibility potential of a large group of buildings.

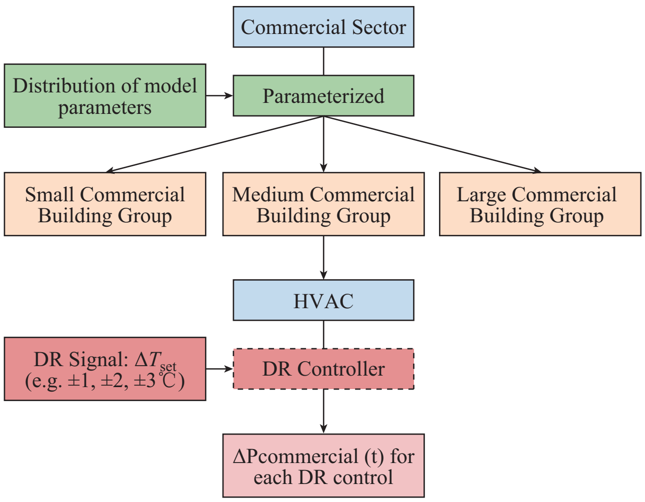

Fig. 5. Framework of demand response estimation presented in [28].

C. Impact of Building Thermal Insulation

One of the findings in [24] and [11] is that the amount of energy flexibility potential is largely influenced by a building's thermal insulation level. This result was in line with the findings in [17]. In the study in [17], flexibility of heating systems of two residential buildings with different level of thermal insulation was conducted with the following conclusions:

1) For poorly insulated buildings, heat flexibility is large, e.g., 25 kWh/m^2 per year, but for a short period, e.g., 2-5 h.

2) For well-insulated buildings, the amount of heat flexibility is small, but the period is long, e.g., heating system can be completely switched off for more than 24 h.

Similar conclusions can be derived when the energy flexibility is evaluated from the electrical grid perspective. For poorly insulated buildings, the thermostatically controlled electric devices can be turned on/off more frequently than the ones installed in well-insulated buildings, resulting in a higher potential of offering services to the power system.

D. Occupancy and Occupant Behaviour and User Perspective

Assessing the potential of BEF requires the consideration of occupant behaviour and building users' decision making [4]. Occupancy and occupant behaviour are the main factors that influence energy consumption in buildings. Conventionally, building simulation tools use static occupancy and occupant behaviour. This method is simple yet fails to capture the stochastic and dynamic characters of occupancy and occupant behaviour. Inaccurate inputs lead to discrepancies between predicted and actual energy consumption. Over the past decades, research work such as [31]–[34] and [35] have studied the patterns of occupancy and occupant behaviour and developed stochastic models, which are available to be integrated with building models for energy performance simulation.

In most studies of BEF, stochastic occupancy and occupant behaviour have not been taken into consideration. In fact, to date, [15] is one of the few published research addressing this issue. The paper presented an approach using Java and EnergyPlus co-simulation for simulating the effect of occupancy, dynamic occupant behaviour, and demand side management on building energy consumption and energy costs. Fig. 6 shows the flow chart of the approach. The Java and EnergyPlus co-simulation method is based on the FMI standard [36]. Java is used to model occupancy and occupant behaviour and serves as a co-simulation manager, while EnergyPlus is used to establish building models and serves as a co-simulation slave. In the case study, the method is applied, considering three type of occupant behaviour: lighting control, plug load control and thermostat control in relation to occupancy, illuminance, and electricity price. The stochastic nature of the energy usage behaviour and occupancy is captured and demonstrated successfully by using this method.

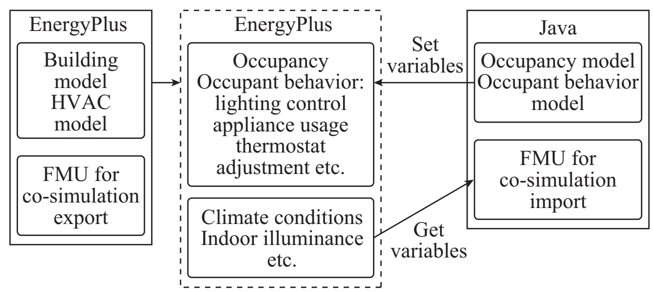

Fig. 6. Dataflow of Java and EnergyPlus co-simulation framework presented in [15].

In the activation and utilization of the potential of building energy flexibility, the users or occupants of the buildings will play an essential role. This is because 1) one of the constraints of energy flexibility is occupants' thermal comfort, 2) occupant behaviour has direct impact on the energy flexibility, 3) building users might have to adopt smart technologies, and thus 4) user technology interaction will increase. As stated in [7], the available flexible demand at any time of the day is subject to the permission being granted by energy consumers to allow access to the loads. The perception of smart grids and energy flexible buildings by building users, and their readiness for them was investigated in [37] on a large scale in the Netherlands. A survey was completed with 785 genuine responses. The results showed that the concept of smart grids was unfamiliar to respondents, with more than 60% of the respondents saying they had never heard of it. Respondents would be most in favour of owning smart dishwashers. Statistical analysis showed that people who are willing to use smart technologies are also willing to use energy in a flexible manner (Fig. 7), and could thus be defined as potentially flexible users. Under certain assumptions, 11% of the respondents were found to be potentially flexible users. The study also suggested that to encourage people to be energy flexible, awareness of smart grids would have to be increased, and the adoption of household smart appliances may have to be promoted by providing financial incentives.

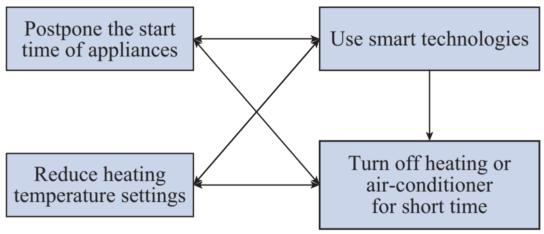

Fig. 7. Interdependencies of willingness to use smart technologies and willingness to be energy flexible, presented in [37].

Another study [7] also concluded that the current market lacks a rewarding algorithm for individual household flexibility. Incentives and the use of smart appliance are necessary for the realization of energy flexibility in buildings.

IV. Aggregation of Buildings' Energy Flexibility

A. Identification and Characterization for Aggregated Energy Flexibility of Buildings

A review of modelling approaches applied to aggregation-based portfolio management is presented in [38]. These approaches use electric vehicles as an example. The structure of an aggregation-based model can include system models (i.e., a portfolio model of flexible components or any relevant system like an electrical network), component models (e.g., batteries and chargers), and process models (e.g., scheduling and control) that link together all models. The selected modelling method and the corresponding complexity of an aggregation model are often dependent on its application and the information available. As for buildings, a literature review of energy performance of building clusters and building stock concluded that the current large-scale demand response studies did not take into account the characteristics of the building and the diversity among buildings, including building type, appliance, thermal characteristics and occupancy, and occupant behaviour [39]. Compared to the approach of using a lumped-model for flexibility characterization, it was suggested in the paper to use archetype-based approach for the diversity. Using this approach, the scaling-up of energy demand could be achieved by multiplying each archetype by the number of buildings represented by each archetype [40]. Regarding modelling techniques, white box modelling has been used to simulate different archetypes, while grey box modelling, specifically RC models show promise for the study of large-scale demand response [39].

B. Examples

A statistical approach for a BEF aggregator to assess and utilize the flexibility of buildings in the electricity market is presented in [41]. The functions of the aggregator are defined as follows:

- Modelling and aggregating the flexible consumption from users and obtaining the reference demand profile and its potential upper and lower bounds;
- Optimizing daily load schedule based on flexibility potential and whole sale market price predictions;
- Submitting the optimal load scheduling to the day-ahead market to minimize the energy cost or maximize its profit.

The demand assessment and aggregation for household was focused on the usage of energy appliances, such as heating, computer use, and cooking, using probabilistic approach. For non-residential buildings, the focus was on HVAC systems. The demand was then estimated based on user profile and appliance usage. In [29] a comprehensive framework for studying electrical flexibility with buildings connected to the grid is presented (Fig. 8). This work presents an optimization framework based on model predictive control (MPC) to control the power flow from the grid, solar photovoltaic panels, and energy storage systems to a commercial building with HVAC systems. The MPC framework uses the inherent thermal mass storage of the building and the energy storage systems as a means to provide demand response. The results show that in addition to decreasing buildings' operational cost, the predictive control framework helps the power grid to employ the flexibility of HVAC systems to prevent problems such as over-generation.

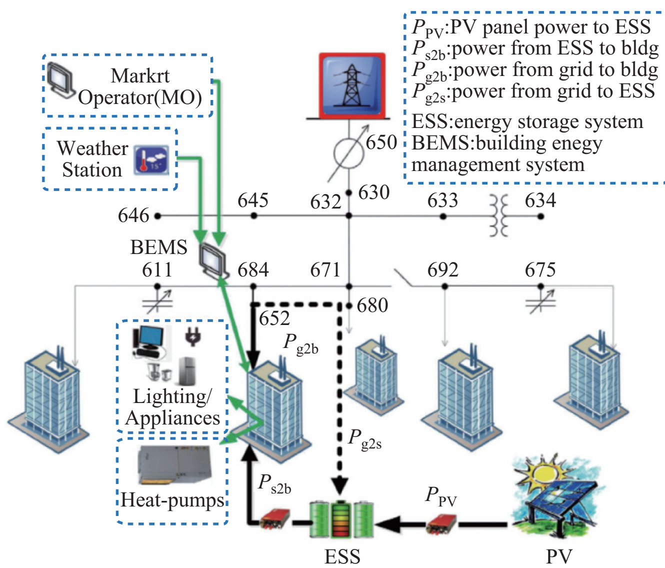

Fig. 8. A building-to-grid system with energy storage and PV for demand response presented in [29].

A data-driven approach is developed by the authors to model energy flexibility of building clusters [48]. Fig. 9 shows the simulation diagram. First, building RC models are developed based on TABULA database [42]. Then statistical data of dwelling size and Danish household size from the Statistics Denmark [43] is used to estimate the number of residents and households in the modelled buildings. Finally, data of Danish time use survey 2008/09 [44] is used as a base to generate occupancy models, which is then assigned to the buildings according to the number of residents. This is rather a generic approach applicable to the simulation of any dwelling types and for the aggregation of any number of dwellings.

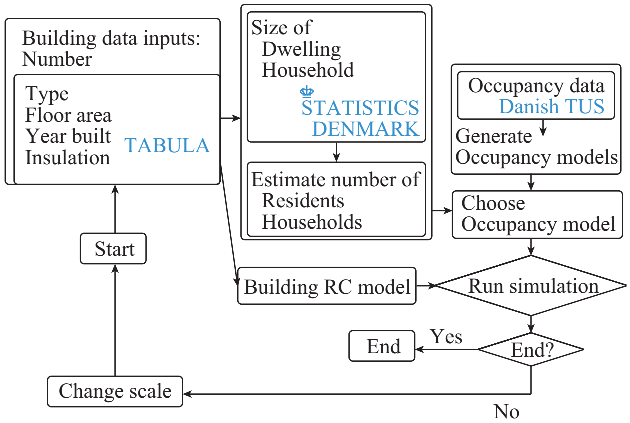

Fig. 9. Flow diagram of quantification of building cluster energy flexibility using data-driven approach [48].

V. Enabling the Application of Buildings' Energy Flexibility through Service-Oriented Solutions

Today, the flexibility offered by demand side energy prosumers (such as buildings with flexible energy potentials) is primarily applied to the electricity sector in Europe through service-oriented solutions. Fig. 10 illustrates a universal smart energy framework (EUSF) defined by the flexibility value chain model. Since the amount of flexibility offered by an individual prosumer is often very limited, it is necessary to have an aggregator who pools together the flexibility offered by a number of flexibility owners in one portfolio in order to scale up the benefits and impact, and to surpass the market entry barriers such as capacity limits. Transmission system operators (TSOs), distribution system operators (DSOs), and balancing responsible parties (BRPs) are the three types of stakeholders who can use flexibility to support their actions as services, given the present market setup and regulatory framework in Europe. For power system operators, the flexibility-based services are also known as ancillary services that are used to support electrical network planning and operation. For BPRs, the flexibility-based services are used to improve their operation economy.

Such an idea of flexibility-based service exchange is already realized by the Danish iPower consortium that developed a flexibility clearing house (FLECH) [8]. Fig. 11 presents how FLECH fits into the present power marketplace in the Nordic area and facilitates the exchange of flexibility-service products and associated information. A number of basic functions of FLECH such as flexibility interface, flexibility clearing algorithm, contract management, and settlement were developed in the iPower project (2011–2016). At the moment, a three-year demonstration project Ecogrid 2.0 (2016–2019) is in the process of demonstrating the FLECH with a number of advanced functions for flexibility acquisition and flexibility management [46]. The objective of Ecogrid 2.0 is to apply FLECH to a real power system, i.e., Bornholm Island, wherein the flexibility is seamlessly integrated into the power system operation through generic market-based platform, flexibility characterization methods.

The value of flexibility can also be exploited from a multi-energy aspect, such as the proposal suggested by the Energy Nordhavn project where a more universal definition of flexibility-based services is referred to as the smart network services (SNSs) [47]. SNSs cover a range of services that can be provided by various flexibility-owning devices. Similarly, flexible systems and infrastructures that are properly designed

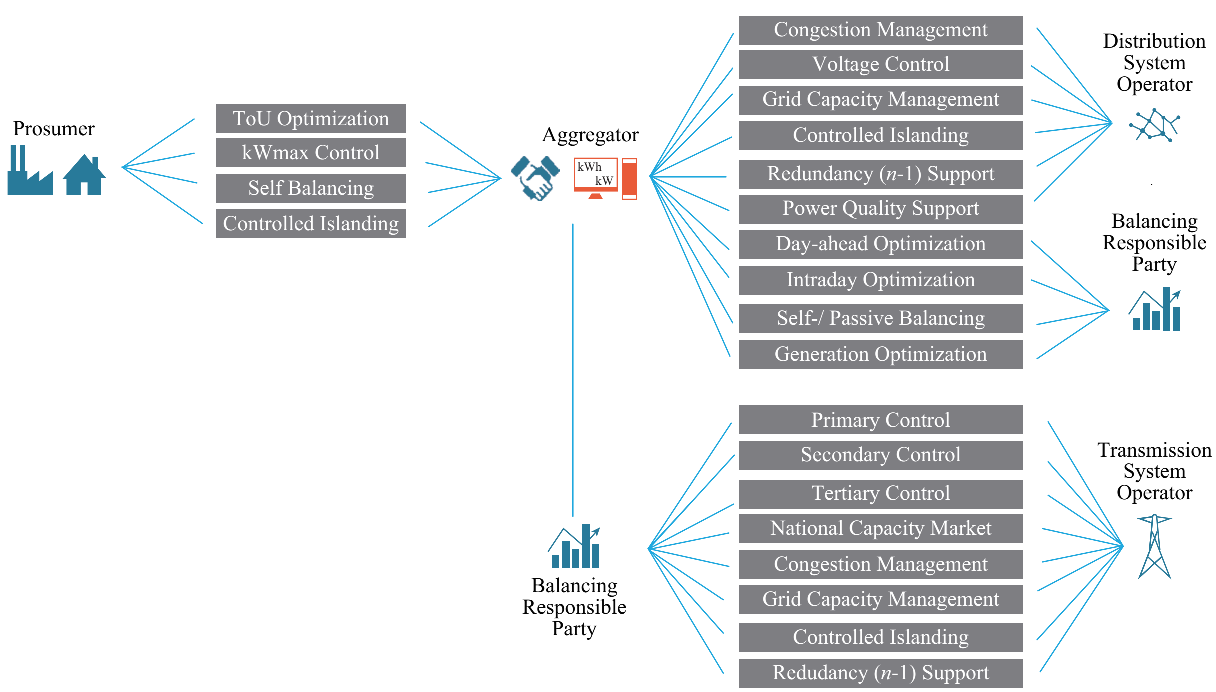

Fig. 10. Flexibility value model defined USEF [45].

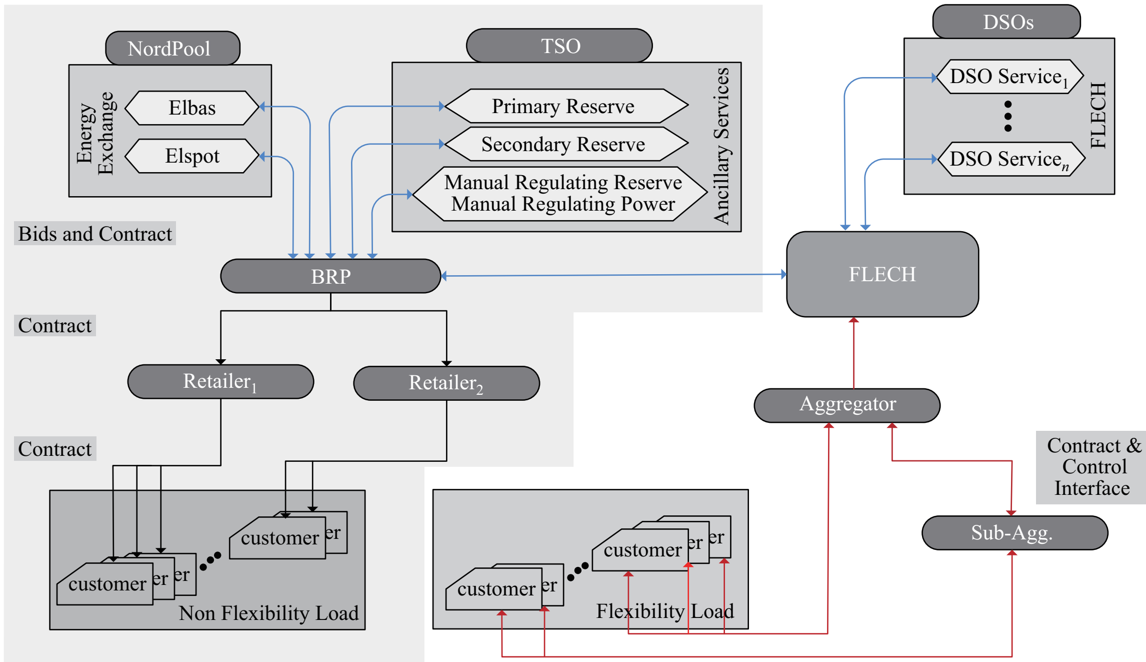

Fig. 11. FLECH in the present power marketplace in Nordic area [8].

can enable technical/market solutions as alternatives to traditional methods for network operations. The term "network" can be interpreted as various types of energy carrier networks, e.g., the electricity distribution network, heat distribution network, gas networks, and E-mobility infrastructure. Several demonstrations have shown that the flexibility offered by energy prosumers can also be used to support the operation of DH systems (e.g., peak shaving or as back up to the main heat supply during maintenance) and cooperative operations between different energy sectors (e.g., the DH system and the electricity distribution system). This way, the unexpected interactions due to the lack of coordination could be mitigated.

VI. Conclusions and Outlook

An overview of the research on energy flexibility in buildings is presented in this paper. The conducted studies characterize the flexibility of buildings from mainly two aspects, i.e., heat and electrical. The study of heat flexibility focuses mainly on energy components, such as hot water storage tanks and building structural thermal mass. The study of electrical flexibility is mainly focused on thermostatically controlled electric devices and non-HVAC electrical appliances inside the buildings.

White box modelling and grey box modelling approaches are commonly used in the process of exploring BEF. White box approach is often based on building simulation software. Grey box modelling, typically RC model, is used when optimization and advanced control are implemented. In addition, white box models are commonly used in the simulation of single building and building archetypes, while grey box models have the potential and advantage to study building clusters. Although there is a growing interest in developing black box models of buildings, data availability and data adequacy are the limitations.

Endogenous factors of buildings such as energy storage, thermal mass, and HVAC system can to a large extent influence the BEF, which are well addressed by the existing studies. Apparently, more research is needed to gain more insights into the exogenous impacts on BEF by factors such as control strategies, occupancy and occupant behaviour, and rewarding schemes.

Developing aggregation-based BEF models and integraing them into service-oriented solutions are the key to enabling the future use of BEF for energy system services in different energy sectors. Several initiations launched in Europe have made the flexibility service-oriented platform close to market; however, the participation from the building side is often narrowed to appliances that are installed inside the buildings. In other words, there is lack of studies that treat the flexibility of buildings as a whole. Transforming the existing building energy management systems into flexibility service-oriented solutions in the future energy system will be one of the major tasks for research institutes and industrial players.

Taking buildings as an active element in the energy system and exploring the corresponding energy flexibility potential for energy system services is a relatively new research area that has been recently initiated and intensively investigated by researchers in Europe and North America. The main drivers behind this initiation are the increasing need for flexibility in the energy system, the reform of energy markets, the fast development of ICT technologies, and the support given to the development of demand side flexibility options. On the contrary, buildings in developing countries such as China are treated as passive energy-consuming units due to the lack of flexibility-oriented supporting schemes and appropriate marketplaces. The development of international joint programs such as IEA EBC Annex 67 would, therefore, play an important role in fostering worldwide designs and applications of using the energy flexibility potential of buildings.

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